

POLLUTION CONTROL APPLICATIONS OF PULSED POWER TECHNOLOGY

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Abstract

Much of the activity and growth in the field of pulsed power technology has been spawned by government-sponsored research for military applications. During the last two decades significant advances have been made in pulsed power modulators and accelerators. Pollution control systems for large industrial applications could benefit a great deal by exploiting the results of this research and development. In this paper I will present the history of how pulsed power technology got involved in pollution control applications. Emphasis will be placed on the application of pulsed power to pollution control in utility and industrial coal-fired power plants. The use of pulsed techniques for improving the efficiency of electrostatic precipitators will first be discussed; then the parallel developments in electron beam and pulsed corona processing for flue gas treatment will be presented. Pulsed power techniques are essential as supporting technologies for these advanced pollution control methods. To illustrate the large scale of these applications, I will discuss the power requirements of these methods.

I. Introduction

Acid rain is now recognized as a serious environmental problem. Nitrogen oxides (NO_x) and sulfur dioxide (SO_2) are mainly responsible for this problem. In the US alone, the total emission of NO_x amounts to 24 million tons per year. About 53% of this is emitted from utility and industrial fuel combustion (see Fig. 1). The total US emissions of SO_2 amounts to 29 million tons per year, 75% of which is emitted from industrial and utility fuel combustion (see Fig. 1). The Clean Air Act of 1990 demands that the NO_x emissions be reduced to 2 million tons per year (92% reduction), and the SO_2 emissions be reduced to 10 million tons per year (66% reduction). The problem of acid rain gas emissions exists, not only in the US, but also worldwide. In the absence of adequate control equipment, the worldwide emissions to the atmosphere are 250 million tons of SO_2 per year and 150 million tons of NO_x per year. In addition there is the problem of solid particulate emissions. Even with particulate removal devices having an average removal efficiency of 99%, the worldwide emission to the atmosphere is still 30 million tons of solid particulates per year. Forecasts suggest that by year 2000, the world coal consumption will increase by 35%. To keep the total emissions of solid particulates constant, the collection surface of electrostatic precipitators have to be doubled.

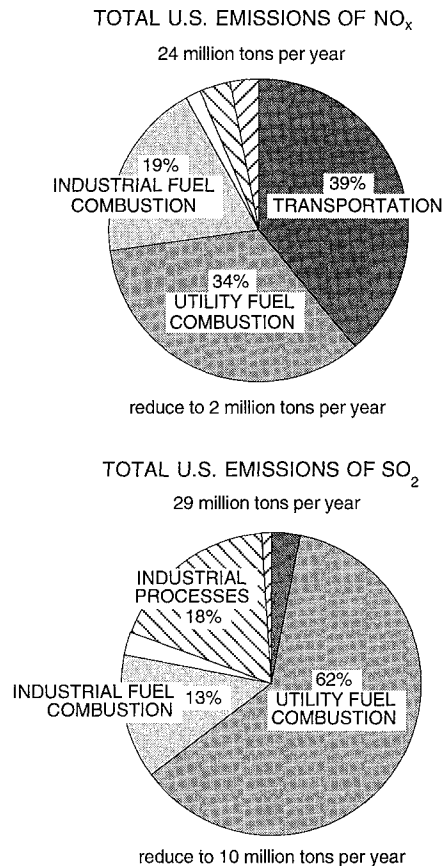


Figure 1. Contributions to the total US emissions of NO_x and SO_2 .

The impact of these pollution problems is aggravated because the emissions are mainly released by point sources clustered together in industrialized countries. There are many methods already available for dealing with these problems. However, the increasing level of emissions and the ever increasing restrictions make it more and more expensive to meet the government regulations designed to protect our environment. Pulsed power technology will become very important in dealing with these environmental problems.

The application of pulsed power to pollution control is not limited to NO_x/SO_2 /particulate removal in power plants. The emphasis of this paper is on the treatment of flue gas emissions from power plants because this is a good example of a very large scale application of pulsed power. This particular application represents a big challenge from the point of view of both the huge market and required technology developments [1].

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II. Historical Overview

In this section I will give a historical overview of how pulsed power technology got involved in pollution control. There are three parallel device developments that make pulsed power an important factor in pollution control: electrostatic precipitation, electron beam processing, and pulsed corona processing. Each of these pollution control methods has been influential in promoting the use of pulsed power.

The commercial implementation of electrostatic precipitation dates back to the developments by F. G. Cottrell in 1905. At the time he used an ac transformer with a mechanical rectifier to supply the high-voltage, unidirectional current required. Today the method and equipment for supplying the high-voltage power still determine in large part the performance of electrostatic precipitators (see Fig. 2).

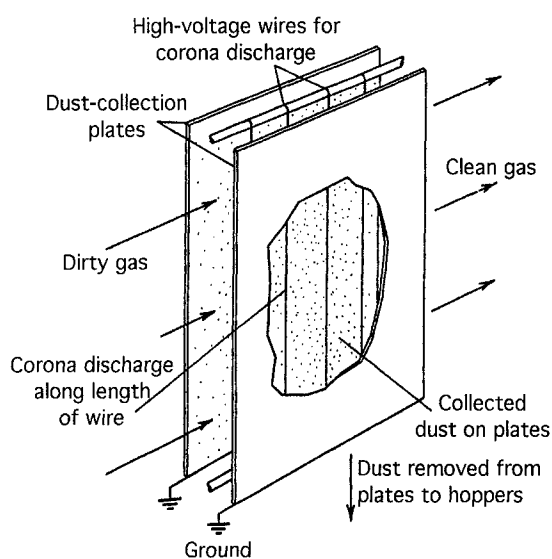


Figure 2. Simplest form of an electrostatic precipitator. When a high voltage is applied to the wire, the electric field created produces a corona region consisting of electrons and ions. The drift field established between the corona region and the collection plate extracts ions. These ions interact with the particulates, imparting charge to the dust which is then driven to the collecting plate. Maximum particle collection requires maximum charges on the particles and maximum precipitation fields. Large particle charges can be attained only by applying very high peak voltages, while rapid collection of the charges requires high time-averaged values of the voltage.

The collection efficiency of electrostatic precipitators increases rapidly with increasing values of the drift velocity of charged particles in the precipitator electric field. The drift velocity increases as the product of the charging field and the collecting field, which in turn, are determined by the voltage waveform. Full-wave and half-wave voltages have higher sparking values than dc voltage and are much more stable in operation. In 1952, H. J. White proposed the use of pulsed systems in electrostatic precipitators [2]. He recognized that pulsed

systems could be used to optimize precipitator efficiency by allowing one to precisely adjust and control both the duration and frequency of the current pulses. The use of pulsed power made it possible to achieve higher peak voltage and higher sparking voltage. He used a rotating spark gap, with 200 - 400 Hz repetition frequency, pulse length of 100 μ s, peak voltage of 70 kV, average current of 300 mA and an output power of 15 kW. This led to an increase in the precipitation efficiency without having to increase the area of the collecting electrodes. Furthermore, White demonstrated that pulsed powering led to a higher over-all electrical efficiency (70%). Unfortunately, attempts to implement pulsed powering was hampered by the available high-voltage switching technology.

In 1970 the Ebara Corporation in Japan conducted the first batch tests of electron beam processing for the simultaneous removal of NO_x and SO_2 from flue gases. In this process, the high energy electrons produce a copious supply of ions and free radicals. The radicals, particularly the OH radical (see Fig. 3), react with SO_2 and NO_x to form sulfuric and nitric acid, respectively. These acids are subsequently neutralized by additives such as ammonia or calcium hydroxide. The resulting by-products are typically dry and can be removed by means of conventional particle collectors such as an electrostatic precipitator or baghouse. With an ammonia additive, the SO_2 and NO_x are converted to ammonium sulfate and ammonium nitrate, which are important agricultural fertilizer components (see Fig. 4).

Between 1970 and 1980, both laboratory and plant tests of electron beam processing were conducted by Ebara, the Japan Atomic Energy Research Institute and the University of Tokyo. Some of these tests were conducted with flue gas flow rates of up to 10,000 Nm^3/h (normal meters cubed per hour). In the USA, Research-Cottrell, in 1979-1980, conducted bench scale tests to evaluate the technical and economical feasibility of electron beam processing.

Between 1981 - 1982, several pilot plant and full-scale tests of pulsed powering for electrostatic precipitators were conducted in both the US and Japan. The US tests showed performance enhancement up to a factor of 3, while the Japanese tests showed performance enhancement up to a factor of 5.

The high capital cost of accelerators and x-ray hazard associated with electron-beam processing motivated studies into alternate plasma-based technologies such as those utilizing electrical discharges. In 1981, S. Masuda led experiments at the University of Tokyo to investigate the possibility of enhancing the NO_x/SO_2 removal efficiency of the electron-beam method by applying an electric field to regenerate energetic electrons in the plasma [3]. It was found that pulsed electric fields could be very effective when a corona discharge was created, even when the electron beam was switched off. This was the birth of the pulsed corona method for flue gas treatment. The pulsed corona method represented an apparently more economical approach by having the advantage of a low retrofit cost since it can use the same wire-plate electrode arrangement as in existing electrostatic precipitators.

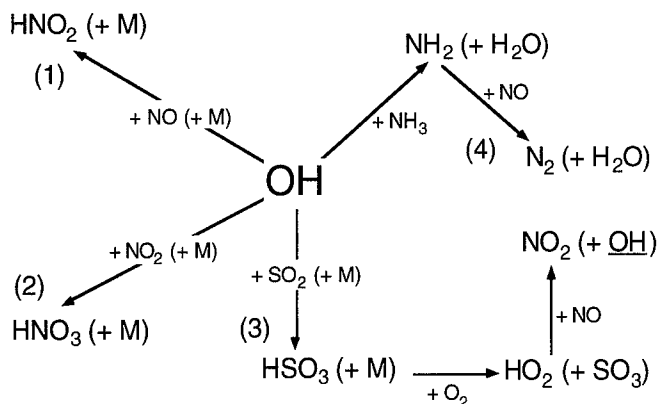


Figure 3. The OH radical plays a key role in the simultaneous removal of NO_x and SO_2 in the presence of water vapor and ammonia. Route (1) is only partially effective, since HNO_2 is liable to heterogeneous decomposition into NO and NO_2 . Route (2) is the most important source of nitric acid and ammonium nitrate. Route (3) replaces OH by HO_2 , which is needed for NO oxidation, and recycles OH. Route (4) replaces OH by NH_2 , which reduces NO. High energy electrons from electron beam irradiation are very effective in producing OH radicals.

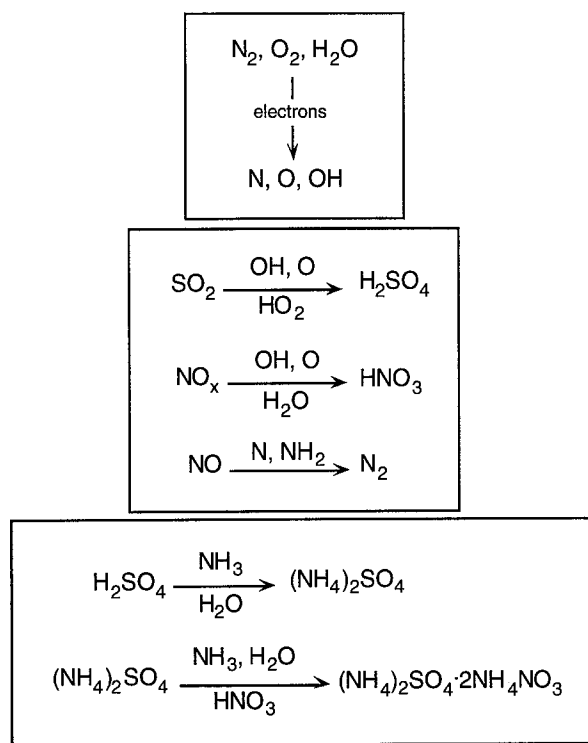


Figure 4. Simplified model of reaction mechanisms for the simultaneous removal of SO_2 and NO_x from flue gas by electron beam irradiation. Stage 1 represents radical production from the interaction of electrons with the flue gas. Stage 2 represents the conversion of SO_2 and NO_x to their respective acids, and the reduction of NO to N_2 . Stage 3 represents the formation of salt by-products which are then collected by an electrostatic precipitator or baghouse. The same mechanisms apply to the pulsed corona process, but the relative amounts of initial radicals and final by-products are different because the mean electron energies are lower.

In 1984 - 1985 pilot plant tests of electron beam processing were conducted in the USA by Research-Cottrell. The tests were done for a coal-fired power plant with flue gas flow rates of up to $5,300 \text{ Nm}^3/\text{h}$. Between 1984 and 1988, the Ebara Environmental Corp. also conducted pilot plant tests of electron beam processing in the USA, with flue gas flow rates of $8,000 - 24,000 \text{ Nm}^3/\text{h}$ from a coal-fired power plant [4]. Also in 1984 - 1985, pilot plant tests of electron beam flue gas treatment were conducted in Germany, with gas flow rates of up to $20,000 \text{ Nm}^3/\text{h}$ from a coal-fired power plant.

Meanwhile in 1985, A. Mizuno from Japan visited Florida State University and collaborated in laboratory-scale studies using the pulsed corona method for the simultaneous removal of NO_x , SO_2 and particulates [5]. At around the same time, the Italian national power company, ENEL, independently conducted small pilot plant tests of pulsed corona processing by retrofitting their electrostatic precipitators. Tests were conducted for a flue gas flow rate of $100 \text{ Nm}^3/\text{h}$ from a coal-fired power plant. Ten electrostatic precipitators of 20 cm diameter and 1.5 m length were used, with voltage pulses of 300 Hz repetition frequency, 600 ns pulse length, risetime of 100 - 300 ns and peak voltage of 90 kV. It is important to note that these ENEL tests have become the sole basis for the assessment of the electrical technology requirements of the pulsed corona process for applications to flue gas cleanup in actual power plants.

In 1985, ENEL tested the pulsed powering of industrial-size electrostatic precipitators [6]. The tests were conducted with flue gas flow rates of $175,000 \text{ Nm}^3/\text{h}$, and used pulses of 300 Hz repetition rate, 60 - 240 μs pulse length, average current of 400 mA and peak voltage of 180 kV. The tests demonstrated precipitator performance enhancement of a factor of 5.

In 1988, ENEL conducted larger pilot plant tests of the pulsed corona process for NO_x/SO_2 removal using a $1,000 \text{ Nm}^3/\text{h}$ flue gas flow rate [7]. The pulses used were 300 Hz, risetime of 200 ns, pulse length of 1 μs , peak voltage of 150 kV and output power of 20 kW. Since that time, ENEL has been working on a scale-up to $10,000 \text{ Nm}^3/\text{h}$, but progress seems to have been hampered by the absence of suitable pulsed power generators (100 kV, 100 kW, 300 Hz, pulse length less than 1 μs , and greater than 75% electrical efficiency).

Back in Japan, three advanced pilot plant tests are now being conducted for electron-beam treatment of flue gases [8]. These tests were started in 1991. One objective of these tests is to optimize the electron beam process for the treatment of flue gases from utility coal-fired boilers. The other objective is to expand the applications of the electron beam process to other kinds of gases; for example, incinerator flue gas, diesel truck exhaust gas, and gases containing various kinds of VOCs. From these pilot projects it is expected that sufficient information will be obtained to design, construct and operate a commercial facility. At the Ebara Corporation research facility in Fujisawa, the electron-beam process is being fine tuned for commercial use, and testing is being performed on

incinerator gases and diesel truck exhaust gases. At the Chubu Electric Plant facility in Nagoya, studies are focused on process optimization, equipment reliability, and by-product handling. At the Tokyo Metropolitan tunnel facility, testing is being done to optimize a high-flow (50,000 Nm³/h), low-NO_x-concentration exhaust gas treatment system in a vehicle tunnel under Tokyo Bay. In addition, the gases are analyzed for other hydrocarbons to determine the effects of the electron-beam process on unburned hydrocarbons.

Large pilot plant tests of electron beam processing also continue to be conducted in other countries. In Poland, tests started in 1991 are being conducted with flue gas flow rates of 20,000 Nm³/h.

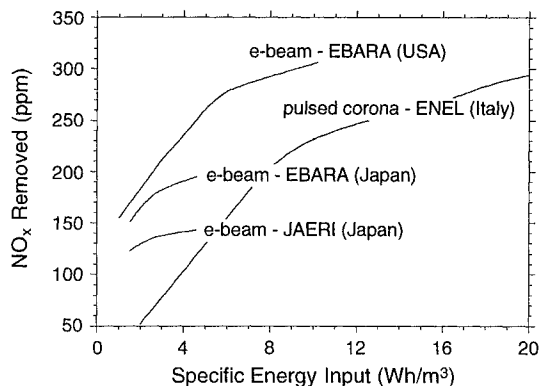


Figure 5. Amount of NO_x removed as a function of the specific energy input. The pulsed corona result obtained at ENEL (Italy) [7] was for initial NO_x of 300-550 ppm, and gas flow rates of 500-600 Nm³/h. The electron beam result obtained at Ebara (USA) [4] was for initial NO_x of 270-390 ppm, and gas flow rates of 4000-5200 scfm. The result obtained at Ebara (Japan) [8] used 3-stage electron beam irradiation with initial NO_x of around 200 ppm. The result obtained at JAERI (Japan) [9] used triple stage irradiation with initial NO_x of 150 ppm and gas flow rate of 15 Nl/min.

III. Power Requirements and Costs

The cost of implementation underlies almost all of the decision-making in selecting the technology for pollution control. Some cost comparison studies show that both the electron beam process and the pulsed corona process are competitive to "conventional" methods. In a recent EPRI study [10], the conclusion was "...for retrofits, the electron beam process rated equivalent or preferable to FGD/SCR (Flue Gas Desulfurization/ Selective Catalytic Reduction)." A study [11] was recently sponsored by the Japanese Ministry of International Trade and Industry to perform technical and economic assessments of the pulsed corona process for coal-burning utility boilers. The pulsed corona process was compared to the conventional calcium-gypsum process for deSO_x combined with the ammonia-catalytic process for deNO_x. A comparison was also made to the electron beam deNO_x/deSO_x process. The study committee concluded that the pulsed corona method deserves development as the next generation technology for the removal of SO₂ and NO_x in utility boiler plants.

In this section I will present the power requirements and cost estimates of both the electron beam process and the pulsed corona process based on the best results achieved in pilot plant tests.

Consider a 500 MW power plant burning 194 tons per hour of midwestern coal. The typical flue gas flow rate is 10⁶ scfm or 4.7x10⁸ cm³/s. The gas is polluted with 350 ppm of NO_x and 2000 ppm of SO₂. Both laboratory and pilot plant tests show that it is relatively easy to remove SO₂. The power consumption for the combined removal of NO_x and SO₂ is determined mainly by the removal of NO_x. The required rate of NO_x removal is

$$350 \text{ ppm} \times 10^{-6} \times 4.7 \times 10^8 \text{ cm}^3/\text{s} \times 2 \times 10^{19} \text{ molecules/s} = 3.3 \times 10^{24} \text{ NO}_x\text{-molecules per second}$$

The best value of specific energy consumption for deNO_x achieved by the electron beam process is

$$14 \text{ eV/NO}_x\text{-molecule} \quad (\text{deNO}_x \text{ by e-beam}).$$

The power requirement for the electron beam process is thus

$$14 \text{ eV/NO}_x \times 3.3 \times 10^{24} \text{ NO}_x/\text{s} = 4.6 \times 10^{25} \text{ eV/s} = 7.4 \text{ MW}$$

This represent 1.5% of the power plant output.

The best value of specific energy consumption for deNO_x achieved by the pulsed corona process is

$$50 \text{ eV/NO}_x\text{-molecule} \quad (\text{deNO}_x \text{ by pulsed corona}).$$

The power requirement for the pulsed corona process is thus

$$50 \text{ eV/NO}_x \times 3.3 \times 10^{24} \text{ NO}_x/\text{s} = 1.7 \times 10^{26} \text{ eV/s} = 26.4 \text{ MW}$$

This represent 5.3% of the power plant output.

Cost analysis shows that in order for electron beam processing to be competitive with the FGD/SCR method, the accelerator has to cost around \$2 per watt. This implies that a 500 MW power plant will require a 7.4 MW accelerator (or set of accelerators) costing \$15 million. Assuming that pulsed power generators can be manufactured at a cheaper cost of \$1 per watt, the same 500 MW power plant will require a 26.4 MW pulsed power system costing \$26 million.

IV. Conclusions

Three points should be noted in the historical overview presented in this paper. First, pulsed power has already been successfully demonstrated in a large scale for improving the efficiency of electrostatic precipitators. Pulsed power will undoubtedly become essential as the world consumption of coal for energy production increases. Second, many pilot plant tests of electron beam processing for NO_x/SO₂ removal have been, and continue

to be, conducted around the world. Coal-fired pilot plant tests with gas flow rates as large as 25,000 Nm³/h have been conducted. Scale-up of electron beam accelerators using pulsed techniques are now being conducted. The use of pulsed power techniques could lead to modular and cheaper electron beam accelerators. Third, demonstration of the pulsed corona process for NO_x/SO₂ removal in a large scale has been hampered by the absence of suitable pulsed power generators. The pulsed power requirements for pulsed corona reactors are much more demanding than those for electrostatic precipitators. The largest pilot plant test conducted by ENEL is 1,000 Nm³/h. As mentioned before, the ENEL tests have become the sole basis for the assessment of the electrical technology requirements of the pulsed corona process. Larger scale tests are essential in order to learn not only what the scalability of the process is, but also what the typical investment and operating costs are at full-scale industrial facilities.

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References

- [1] G. Lister, "Plasmas Join the Fight Against Acid Rain," Physics World (Dec. 1992) pp. 19-20.
- [2] H. J. White, "A Pulse Method for Supplying High-Voltage Power for Electrostatic Precipitation," AIEE Trans. vol. 71, pp. 326-329 (1952).
- [3] S. Masuda, M. Hirano, and K. Akutsu, "Enhancement of electron beam denitration process by means of electric field," Radiat. Phys. Chem. vol. 17, pp. 223-228 (1981).
- [4] N. W. Frank and S. Hirano, "The History of Electron Beam Processing for Environmental Pollution Control and Work Performed in the United States," presented at the NATO Advanced Research Workshop on Non-Thermal Plasma Techniques for Pollution Control, Cambridge, UK, Sep. 21-25, 1992.
- [5] A. Mizuno and J. S. Clements, "Method of Removing SO₂, NO_x and Particles from Gas Mixtures Using Streamer Corona," U.S. Patent Number 4,695,358 (Sep. 22, 1987) Assignee: Florida State University.
- [6] G. Dinelli and M. Rea, "Pulse Power Electrostatic Technologies for the Control of Flue Gas Emissions," J. Electrostatics vol. 25, 23-40 (1990).
- [7] G. Dinelli, L. Civitano, and M. Rea, "Industrial Experiments on Pulse Corona Simultaneous Removal of NO_x and SO₂ from Flue Gas," IEEE Trans. Ind. Appl. vol. 26, pp. 535-541 (1990).
- [8] A. Maezawa and M. Izutsu, "Application of E-Beam Treatment to Flue Gas Cleanup in Japan," presented at the NATO Advanced Research Workshop on Non-Thermal Plasma Techniques for Pollution Control, Cambridge, UK, Sep. 21-25, 1992.
- [9] O. Tokunaga and H. Namba, "Experiments of Chemical Reactions in Electron-Beam-Induced NO_x/SO₂ Removal," presented at the NATO Advanced Research Workshop on Non-Thermal Plasma Techniques for Pollution Control, Cambridge, UK, Sep. 21-25, 1992.
- [10] Pasha Publications (Dec. 23, 1991), Coal & Synfuels Technology, Source: Electric Power Research Institute.
- [11] "Study Report on Novel Dry DeNO_x/DeSO_x Technology for Cleaning Combustion Gases from Utility Thermal Power Plant Boilers Using Pulse Corona Induced Plasma Chemical Process," Association of Mechanical Industries Japan, Research Institute of Energy Engineering (May 1991).